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Voltage Drop Compensation and Congestion Management by Optimal Placement of UPFC

Saber Izadpanah Tous [1], Somayeh Hasanpour [2]
[1] Department of electrical engineering, Sadjad Institute for Higher Education, Mashhad, Iran
[2] Assistant Professor, Department of electrical engineering, Sadjad Institute for Higher Education, Mashhad, Iran
Email: s.izadpanah220@sadjad.ac.ir

(Abstract) This paper proposes an approach to detect the optimal placement of Unified Power Flow Controller (UPFC) to voltage drop compensation and reduce congestion. To find the location of shunt part of UPFC, we proposed new indices to voltage drop compensation. Also congestion rent contribution method used to determine the location of series part of UPFC. In order to reduce the solution space, we will establish a priority list. UPFC allows concurrent control of active and reactive power flow and voltage amplitude at the UPFC terminals. These specifications give UPFC the ability to improve the efficiency of the power system during various operating situations. For the case studies, 23-bus test system is selected and a UPFC is placed in the system. Simulation results show that the proposed method is able to detection the optimal placement of UPFC. Also simulation results show that with the installation of UPFC in network, voltage drop due to increasing the load is compensated and total congestion cost is decreased.

Keywords: Congestion; Locational Marginal Price (LMP); Total Voltage Drop Index (TVDI); Total Voltage Drop of Network Index (TVDNI); UPFC; Voltage Drop Compensation; Voltage Drop Index (VDI).

1. NOMENCLATURE

x_k	The series transformer reactance.
r_{max}	The maximum value of injected voltage amplitude (p.u.).
S_B	The system base power.
$S_S = S_{conv2}$	The nominal rating power of the series converter.
r	The value of injected voltage amplitude (p.u.).
γ	The value of injected voltage angle.
n	The number of buses connected to load (without generator).
m	The Number of steps to increase the network load.
	The Number of candidate buses.
$V_{i,j}$	The voltage amplitude of bus in the stage of the increased network load ($V_{i,0}$: Voltage amplitude of bus in the base case).
P_{ij}	The power flow between buses *i* and *j*.
N_L	The total number of lines.
LMP_i, LMP_i	The Locational Marginal Price at buses *i*. and *j* respectively
CC_{ij}	The congestion cost of line *ij*.
CCC_{ij}	The congestion rent contribution of line *ij*.

2. INTRODUCTION

Voltage drop compensation is a significant issue in electrical power systems. Since the voltage drop can be compensated by controlling the reactive power, shunt and shunt-series Flexible AC Transmission Systems (FACTS) devices play a great role in controlling the reactive power flow to the power systems. Also FACTS devices can decrease power losses, improve voltage profiles, control transmission power flow and control power demanded from the power networks.

Many papers have been presented on the optimal placement of FACTS devices in order to voltage drop compensation. In [1], PSO (Particle Swarm Optimization) technique has been proposed for determining the optimal placement of SVC (Static Var Compensator) in order to voltage stability enhancement under contingency condition. In [2], HSA (Harmony Search Algorithm) and GA (genetic algorithm) are used for optimal placement of FACTS devices considering voltage stability and losses. In [3], the objective functions include congestion management and improve voltage stability. In [4], the placement of FACTS devices in order to enhance voltage based on PSO technique. In [5] and [6], placement of FACTS devices has been done for voltage profile improvement.

Transmission congestion problem is another important issue in the power network. Congestion occurs when there is insufficient transmission capacity to satisfy the required power all loads. As well as another reason for the congestion is emergency conditions such as outage of lines and generators. The best solution to reduce congestion (or congestion management) is use of FACTS devices to control power flow. The series FACTS devices such as Thyristor Controlled Series

Compensator (TCSC) and Static Synchronous Series Compensator (SSSC) are suitable to congestion management. There are many papers for finding the optimal locations of the UPFC to congestion management [7] - [10].

The main problem about the FACTS devices is high cost of installing these devices. Therefore, the best placement of installation these devices should be well determined.

The rest of the paper is organized as follows: static model and performance of UPFC is described in section III. The proposed placement methodology for UPFC is presented in Section IV. Simulation results along with some observations are discussed in Section V. In this section 23-bus test system is used for the case studies. The paper ends with a summary conclusion in the final section.

3. STATIC MODEL OF UPFC

The Unified Power Flow Controller is the perfect device among the FACTS devices. The structure of UPFC that shown in Figure 1, consisting of two "back to back" AC to DC voltage source converters (VSC) operated from a common DC link capacitor. First converter (converter 1 or shunt converter) is connected in shunt and the second converter (converter 2 or series converter) in series with the transmission line [11], [12].

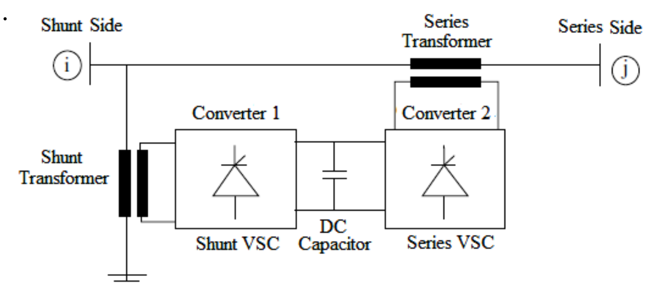

Figure 1. Structure of UPFC.

The shunt converter is mainly used to supply active power demand of the series converter via a common DC link. Converter 1 can also generate or absorb reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line. Converter 2 provides the basic function of the UPFC by injecting a voltage with controllable amplitude and phase angle in series with the line via a voltage source, Figure 2.

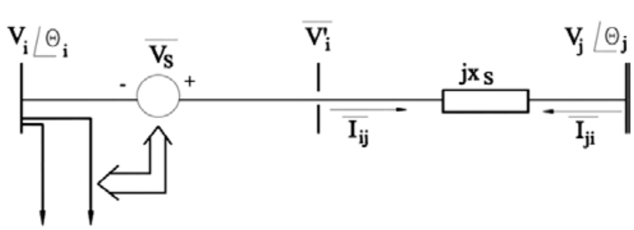

Figure 2. The UPFC electric circuit [12].

The reactance x_s describes a reactance seen from terminals of the series transformer and is equal to (in p.u. base on system voltage and base power) [11], [12]:

$$x_s = x_k r_{max}^2 \left(\frac{S_B}{S_S}\right) \tag{1}$$

$$b_s = -\frac{1}{x_s} \tag{2}$$

Voltage source connected in series is modeled with an ideal series voltage ($\overline{V_s}$) the amplitude and phase is controlled [11], [12].

$$\begin{aligned} &\overline{V_s} = r\overline{V_i}e^{j\gamma} \\ &0 \le r \le r_{max} \\ &0 \le \gamma \le 2\pi \end{aligned} \tag{3}$$

The equations of the UPFC injection model (Figure 3) are given as [11], [12]:

$$P_{si} = -rb_sV_iV_j\sin(\theta_i - \theta_j + \gamma) \tag{4}$$

$$Q_{si} = -rb_sV_i^2\cos(\gamma) + Q_{conv1} \tag{5}$$

$$P_{sj} = rb_sV_iV_j\sin(\theta_i - \theta_j + \gamma) \tag{6}$$

$$Q_{sj} = rb_sV_iV_j\cos(\theta_i - \theta_j + \gamma) \tag{7}$$

$$\begin{aligned} P_{i1} = &-rb_sV_iV_j\sin(\theta_i - \theta_j + \gamma) \\ &- b_sV_iV_j\sin(\theta_i - \theta_j) \end{aligned} \tag{8}$$

$$\begin{aligned} Q_{i1} = &-rb_sV_i^2\cos(\gamma) + Q_{conv1} - b_sV_i^2 \\ &+ b_sV_iV_j\cos(\theta_i - \theta_j) \end{aligned} \tag{9}$$

$$\begin{aligned} P_{j2} = &\ rb_sV_iV_j\sin(\theta_i - \theta_j + \gamma) \\ &+ b_sV_iV_j\sin(\theta_i - \theta_j) \end{aligned} \tag{10}$$

$$\begin{aligned} Q_{j2} = &\ rb_sV_iV_j\cos(\theta_i - \theta_j + \gamma) - b_sV_j^2 \\ &+ b_sV_iV_j\cos(\theta_i - \theta_j) \end{aligned} \tag{11}$$

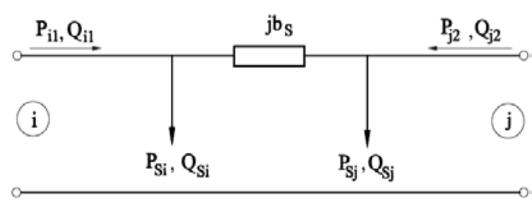

Figure 3. Injection model of the UPFC [12].

4. PLACEMENT OF UPFC

4.1. Voltage Drop Compensation

In this paper to determine the optimal placement of shunt part of UPFC in order to voltage drop compensation, three indices have been presented [13].

I. Voltage Drop Index (VDI)

This index represents the value of voltage drop in any buses.

$$\begin{aligned} &VDI_{i,j} = \frac{|V_{i,j} - V_{i,j-1}|}{V_{i,j-1}} \\ &for \quad i=1,\ldots,n \quad j=1,\ldots,m \end{aligned} \tag{12}$$

II. Total Voltage Drop Index (TVDI)

This index represents the total voltage drop for any buses at all the stages change the network load. This index is used for ranking the buses.

$$TVDI_i = \sum_{j=1}^{m} VDI_{i,j} \tag{13}$$

for $i = 1, \ldots, n$ and $j = 1, \ldots, m$

III. Total Voltage Drop of Network Index (TVDNI)

This index represents the total voltage drop at the first stage increase the network load. Also this index is used to select the optimal placement of UPFC and will be calculated only for candidate buses.

$$TVDNI_c = \sum_{i=1}^{n} VDI_{i,1} \tag{14}$$

for $i=1,\ldots,n$ *and* $c=1,\ldots,l$

The proposed algorithm to determine best location for installing shunt part of UPFC is shown in Figure 4.

The following criteria have been used for optimal placement of UPFC.

- The lines having transformers have not been considered for the UPFC placement.
- The buses having generator have not been considered for the UPFC placement.

In this article we consider a uniform load growth in all network buses, with k%.

4.2. Congestion Management

To determine the location of installing shunt part of UPFC, we used congestion rent contribution method [14]. The congestion rent of the line ij is expressed as follows:

$$CC_{ij} = |LMP_i - LMP_j| * P_{ij} \tag{15}$$

The total congestion rent is expressed as follows:

$$TCC = \sum_{ij=1}^{N_L} CC_{ij} \tag{16}$$

The congestion rent contribution of the line *ij* is defined as:

$$CCC_{ij} = \frac{CC_{ij}}{TCC} \tag{17}$$

Procedure of the congestion rent contribution method is summarized in the following eight steps:

1- Run the base case Optimal Power Flow (OPF) to calculate the LMP at all buses and the power flow between buses i and j.
2- Calculate Equation (15) to all lines.
3- Calculation Equation (16)
4- Calculation congestion rent contribution using Equation (17) to all lines.
5- Ranking of lines based on highest value of CCC_{ij}.
6- Installation of UPFC at the candidate lines and run OPF.
7- Calculation total congestion rent after installing the UPFC.
8- The optimal placement of series part of UPFC is the one where by installing UPFC gives the minimum total congestion cost.

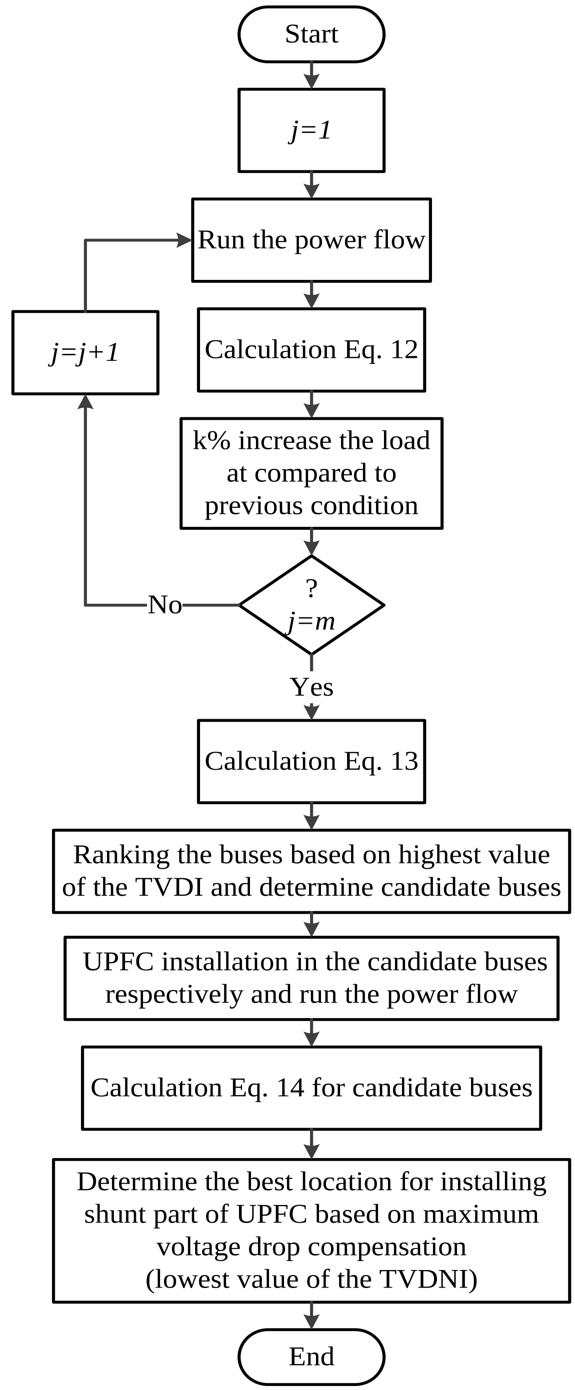

Figure 4. Flow chart of the proposed algorithm.

5. SIMULATION RESULTS

The proposed method for optimal placement of UPFC has been tested on 23-bus system. The system data and single line diagram is found in Appendix A. It consists of five synchronous machines. There are 17 loads in the system totaling 834 MW and 465 Mvar. 23-bus system will be modeled and simulated by

using NEPLAN software [15]. In this article m=2 and k=10 have been selected.

5.1. Voltage Drop Compensation

Table 1 shows the power flow result before increase the network load.

Table 1. Power Flow Result Before Increase the Network Load.

Bus number	Voltage amplitude (%) Base case ($V_{(i,0)}$)
1	100
2	100
3	93.7
4	90.88
5	94.61
6	100
7	99.82
8	96.32
9	99.99
10	100
11	97.75
12	95.84
13	95.26
14	94.48
15	93.89
16	94.08
17	93.85
18	94.28
19	99.99
20	100
21	100.58
22	102.66
23	103

Table 2 and 3 shows the results of calculation of VDI for j=1 and j=2 respectively.

Table 2. Voltage Drop Index for J=1

Bus number	(j=1)	
	Voltage amplitude (%)	$VDI_{i,1}$ (%)
3	92.77	0.99
4	88.86	2.22
5	92.09	2.66
7	99.7	0.12
8	92.86	3.59
9	99.95	0.04
11	96.71	0.96
12	93.61	2.33
13	92.54	2.86
14	91.73	2.91
15	91.17	2.9
16	92.09	2.12
17	91.39	2.62
18	92.92	1.44
19	99.99	0
21	100.38	0.2
22	102.59	0.07

Table 3. Voltage Drop Index for J=2

Bus number	(j=2)	
	Voltage amplitude (%)	$VDI_{i,2}$ (%)
3	90.57	2.37
4	83.33	6.22
5	84.41	8.34
7	99.39	0.31
8	81.73	11.99
9	99.81	0.14
11	94.03	2.77
12	87.66	6.36
13	85.18	7.95
14	84.56	7.82
15	84.19	7.66
16	87.26	5.24
17	85.49	6.46
18	90.09	3
19	99.98	0.01
21	100.12	0.26
22	102.46	0.13

The TVDI, as derived in equations (13), have been obtained and given in Table 4. The top 6 ranks, in their order, have been given in column 3 based on Total Voltage Drop Index which are given in 2th column.

Table 4. Rank Orders based on TVDI

Bus number	$TVDI_i$ (%)	Priority number
3	3.36	
4	8.44	
5	11	2
7	0.43	
8	15.49	1
9	0.18	
11	3.73	
12	8.69	
13	10.81	3
14	10.73	4
15	10.56	5
16	7.36	
17	9.08	6
18	4.44	
19	0.01	
21	0.46	
22	0.2	

According to the Table 4, buses 8, 5, 13, 14, 15 and 17 are chosen for installing shunt transformer of UPFC respectively.

5.2. Congestion Management

Table 5 shows the OPF result (LMP, P_{ij}, CC_{ij} and CCC_{ij}) without UPFC. According to the Table V, lines 17-18, 8-9, 18-19, 4-5, 15-16 and 5-8 are chosen for installing series transformer of UPFC respectively. According to Table 4 and 5, the suitable locations for installing UPFC shown in Table 6.

Table 5. Optimal Power Flow Result

Priority List	CCC_{ij}	CC_{ij} ($/h)	P_{ij} (MW)	LMP Difference ($/MWh)	Location (Line)	LMP ($/MWh)	Bus Number
	0	0	------	0	1-2	63.9	1
	0.063	357.192	99.22	3.6	2-3	63.9	2
	0.0006	3.352	1.635	2.05	3-4	67.5	3
4	0.1	574.6	52.094	11.03	4-5	69.55	4
	0.026	148.057	31.772	4.66	5-7	58.52	5
6	0.073	414.712	81.316	5.1	5-8	53.86	6
	0	0	------	0	6-7	53.86	7
	0.0064	36.528	53.718	0.68	7-11	53.42	8
2	0.193	1096.249	135.006	8.12	8-9	45.3	9
	0.0125	70.878	40.97	1.73	8-13	45.3	10
	0	0	------	0	9-10	54.54	11
	0.0016	8.967	15.461	0.58	11-12	55.12	12
	0.00017	0.957	31.908	0.03	12-13	55.15	13
	0.0019	10.92	32.117	0.34	13-14	55.49	14
	0.0032	17.99	59.96	0.3	14-15	56.19	15
	0.061	346.332	74.488	4.65	14-17	35.59	16
5	0.073	415.09	20.15	20.6	15-16	50.84	17
	0.0144	81.63	70.983	1.15	16-22	42.04	18
1	0.196	1113.34	126.516	8.8	17-18	38.09	19
3	0.148	839.77	212.6	3.95	18-19	38.09	20
	0	0	------	0	19-20	37.5	21
	0.012	68.98	116.915	0.59	19-21	36.74	22
	0.0127	72.262	95.081	0.76	21-22	36.74	23
	0	0	0	0	22-23		
	TCC = 5677.806($/h)						

Table 6. Locations for Installing UPFC

Location of UPFC installation		Series part of UPFC	Shunt part of UPFC
Line	Bus	Location (Line)	Bus number
8-9, 8-5	8	17-18	8
5-8, 5-4	5	8-9	5
15-16	15	18-19	13
17-18	17	4-5	14
		15-16	15
		5-8	17

Table 7 shows the results of calculation of TVDNI for the candidate buses after installation of UPFC.

Table 7. TVDNI for Candidate Buses

Bus number to installation of UPFC	$TVDNI_c$ (%)
8	1.369
5	6.9
15	2.32
17	5.64

Also Table 8 shows the results of calculation of TCC for the candidate lines after installation of UPFC.

Table 8. TCC After Installation of UPFC in Candidate Lines

TCC ($/h) Without UPFC	TCC ($/h) With UPFC	Location (Line)
5677.806	4272.46	8-9
	5068.91	8-5
	4413.3	5-4
	5169.7	15-16
	5294.82	17-18

For 23-bus system, according to the Table 7 and 8 the optimal placement of UPFC is found as bus 8 and line 8-9. Shunt transformer to the bus 8 and series transformer to the line 8-9 has been installed. Power flow results for UPFC Installed at bus 8 and line 8-9 are given in Table 9. As you can see with installation UPFC would yield a more satisfying result which has improved the voltage amplitude compared to condition before the installation of UPFC.

Also optimal power flow results after installation of UPFC are given in Table 10. According to Table 10 total congestion cost than the case without UPFC is reduced.

6. CONCLUSION

The present paper focuses on demonstrating a technique for optimal location of UPFC to voltage drop compensation. Voltage drop, Total Voltage Drop and Total Voltage Drop of Network indices and congestion rent contribution method are presented for locating UPFC.

The presented method is tested on 23-bus system. The results show the capability of the suggested algorithm to optimal placement of UPFC. The simulation results show the optimal placement of UPFC causes reduction in the total congestion and compensation the voltage drop. Benefits of the proposed method are easily for use, runs on any network and use for different types of FACTS devices.

Table 9. Power Flow Results for UPFC Installed at Bus 8 and Line 8-9

Bus number	**Voltage amplitude (p.u.) Base case ($V_{(i,0)}$)**	**Voltage amplitude (p.u.) j=1**		**Voltage amplitude (p.u.) j=2**	
		With UPFC	$VDI_{i,1}$ **(%)**	**With UPFC**	$VDI_{i,2}$ **(%)**
3	0.937	0.9377	[illegible]	0.9321	0.6
4	0.9088	0.9171	[illegible]	0.9085	0.94
5	0.9461	0.9651	[illegible]	0.9596	0.57
7	0.9982	0.9985	[illegible]	0.9979	0.06
8	0.9632	1	[illegible]	1	0
9	0.9999	0.9999	0	0.9994	0.05
11	0.9775	0.9783	[illegible]	0.9713	0.71
12	0.9584	0.9619	[illegible]	0.9475	1.5
13	0.9526	0.9578	[illegible]	0.9406	1.8
14	0.9448	0.9465	[illegible]	0.9268	2.08
15	0.9389	0.9394	[illegible]	0.9192	2.15
16	0.9408	0.9384	0.255	0.9219	1.76
17	0.9385	0.935	0.373	0.9143	2.21
18	0.9428	0.9377	0.54	0.9249	1.365
19	0.9999	0.9999	0	0.9998	0.01
21	0.10058	1.004	0.18	1.0018	0.22
22	0.10266	1.0264	0.019	1.0258	0.058
$TVDNI$ **(%) With UPFC**		1.369		16.083	
$TVDNI$ **(%) Without UPFC**		28.03		76.751	

Table 10. Optimal Power Flow Results for UPFC Installed at Bus 8 and Line 8-9

CC_{ij} **($/h)**	P_{ij} **(MW)**	**LMP Difference ($/MWh)**	**Location (Line)**		**LMP ($/MWh)**	**Bus Number**
0	------	0	1-2		63.55	1
76.48	96.81	0.79	2-3		63.55	2
13.46	4.019	3.35	3-4		64.34	3
299.3148	54.52	5.49	4-5		60.99	4
57.3216	25.59	2.24	5-7		55.5	5
255.3322	81.316	3.14	5-8		53.26	6
0	------	0	6-7		53.26	7
29.0077	53.718	0.54	7-11		52.36	8
735.0109	90.016	4.88	8-9		47.48	9
137.75	49.372	2.79	8-13		47.48	10
0	------	0	9-10		53.8	11
2.409	6.692	0.36	11-12		54.16	12
9.32	9.414	0.99	12-13		55.15	13
21.535	31.669	0.68	13-14		54.47	14
97.36	59.73	1.63	14-15		56.1	15
310.8	74.71	4.16	14-17		35.52	16
419.42	20.38	20.58	15-16		50.31	17
91.153	71.213	1.28	16-22		41.91	18
1064.666	126.746	8.4	17-18		38.09	19
813.186	212.876	3.82	18-19		38.09	20
0	------	0	19-20		37.53	21
65.378	116.747	0.56	19-21		36.8	22

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Appendix A

The 23-bus test system date that shown in Figure A. 1 is given in Tables A. 1– A. 5.

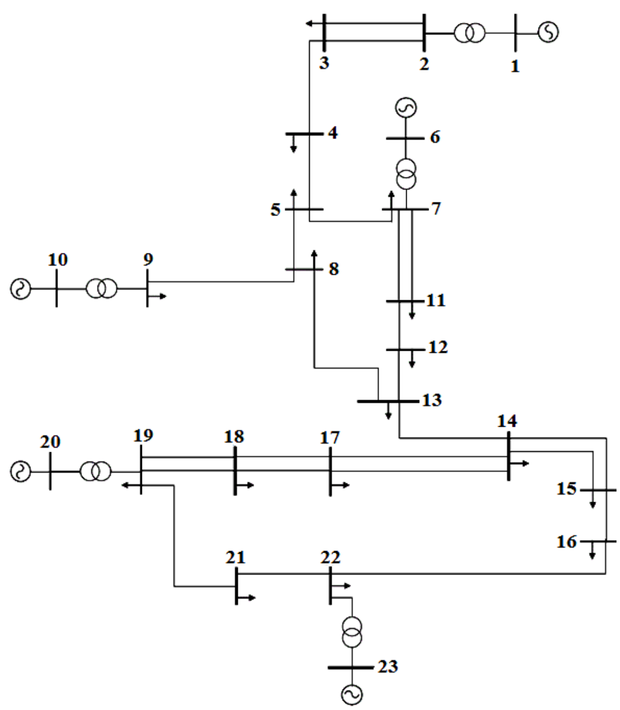

Figure A.1. Optimal Power Flow Results for UPFC Installed at Bus 8 and Line 8-9

Table A. 1. Load Data

Bus Number	Active Power (MW)	Reactive Power (Mvar)
3	100	50
4	50	40
5	60	30
7	11	5
8	10	5
9	10	5
11	38	20
12	16	10
13	8	2
14 (Total scaling factor for P and Q =0.5)	92→46	30→15
15	80	30
16	50	50
17	50	40
18	83	80
19	75	30
21	20	20
22	127	33

Table A. 2. Generator Data

Bus Number	Voltage Magnitude (p.u.)	Generation (MW)	MW Limits		Mvar Limits		Generation Cost		
			Min	Max	Min	Max	a (US$/MW^{2}h)	b (US$/MWh)	c (US$/h)
1 (PV)	1	200	0.1	100000	-100000	100000	0.07	50	0
6 (PV)	1	110	0.1	100000	-10000	100000	0.02	50	0
10 (slack)	1.0	-----	0.1	100000	-100000	100000	0.07	25	0
20 (PV)	1	250	0.1	100000	-100000	100000	0.01	30	0
23 (PV)	1.03	200	0.1	100000	-100000	100000	0.08	20	0

Table A. 3. Transformer Data

Buses Number	Rated voltage of the primary (kV)	Rated voltage of the secondary (kV)	Rated power (MVA)	Rated positive sequence short circuit voltage (%)	Vector Group
2-1	220	20	5000	0.1	yd5
7-6	220	20	3000	9.57	yd5
9-10	220	20	3000	3.36	yd5
19-20	220	20	10000	1.5	yd5
22-23	220	20	1500	6.18	yd5

Table A. 4. Bus Data (Frequency=50Hz)

Bus Number	Nominal voltage (kV)	Min. allowable node voltage (%)	Max. allowable node voltage (%)
1, 6, 10, 19, 20, 23	20	95	110
Other buses	220	95	110

Table A. 5. Line Data

Buses Number	Length (km)	R (ohm/km)	X (ohm/km)	B (uS/km)	Maximum rated current (A)
2-3	216.3	0.028	0.32	1.3	0
2-3	216.3	0.028	0.32	1.3	0
3-4	236.7	0.02	0.3	1.3	80
4-5	248.2	0.03	0.3	1.25	200
5-7	300.5	0.0282	0.3231	1.351	0
5-8	151.6	0.032	0.31	1.31	300
7-11	120	0.04	0.32	1	0
7-11	120	0.04	0.32	1	0
8-9	319.2	0.022	0.33	1.36	0
8-13	273.9	0.02	0.2	1.15	200
11-12	100	0.0295	0.29	1.2	140
12-13	43.4	0.015	0.31	1.351	120
13-14	30	0.03	0.38	0.9	200
14-15	59.4	0.024	0.32	1.3	120
14-15	59.4	0.024	0.32	1.3	120
14-17	320.9	0.0282	0.3231	1.351	180
14-17	320.9	0.0282	0.3231	1.351	180
15-16	248.2	0.02	0.22	0.8	60
16-22	212.8	0.026	0.37	1.4	300
17-18	432.6	0.026	0.29	1.1	300
17-18	432.6	0.026	0.29	1.1	300
18-19	219	0.027	0.34	1	0
18-19	219	0.027	0.34	1	0
19-21	229.6	0.03	0.3	1.3	0
21-22	291.7	0.032	0.28	1	300